



Safety Performance of Small Lithium-Ion Cells in High Voltage Batteries

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Introduction



- Small-cell EAPU work done by NASA-JSC & COM DEV
- Looking at safety features – short circuit protection - PTCs
- Early tests showed that long strings do not withstand short circuit
 - Some PTCs experience large negative voltages
 - Destructive results
- **Solution:** group cells into shorter substrings, with bypass diodes
- Work included:
 - Tests with single cells shorted
 - Tests with single cells with imposed negative voltages
 - 6s, 7s and 8s string shorts
 - Tests with protection scheme in place, on 12s and 41s x 5p

Specific Requirements

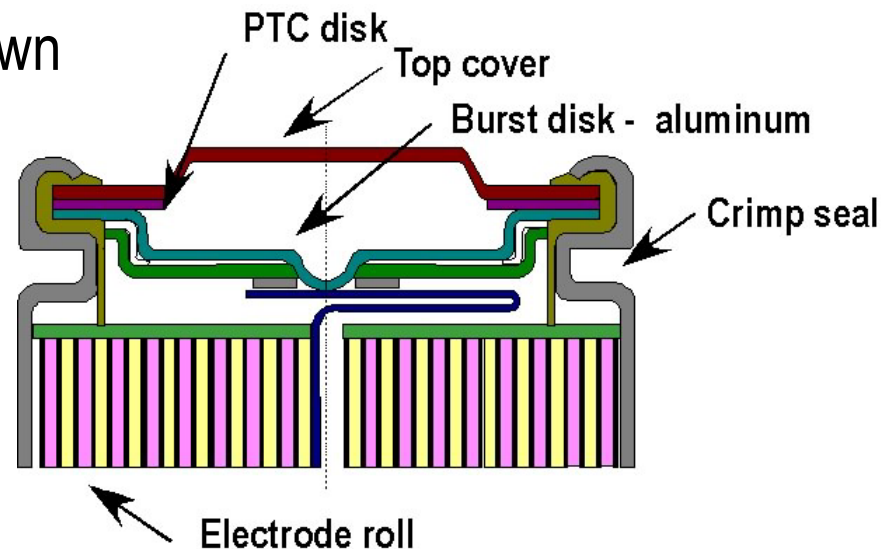


- NASA requires a '2-failure tolerance' against catastrophic failure
 - Fire, explosion, severe venting
- One failure is an external short-circuit
The other a is failure in a cell that might propagate
- Not a usual requirement for unmanned missions
 - Most spacecraft primes have a fuse-blowing or fault clearance target
 - e.g. 2000 Amp for 20 mS
- Most obvious case is a hard short at or close to the terminals
- We also consider the case of a 'smart short'
 - defined as a low-resistance short that is more damaging than a hard short

The nature of a Shorted String



- Use fully charged cells (4.4V/cell)
- >60 amp/string inrush current
- Sony cells have a PTC device
- In a long string, all PTC's race to trip
- The winner gets a high negative voltage
- More than ~30V and it breaks down
- This implies strings of $\sim > 7s$ will not be protected by the PTCs

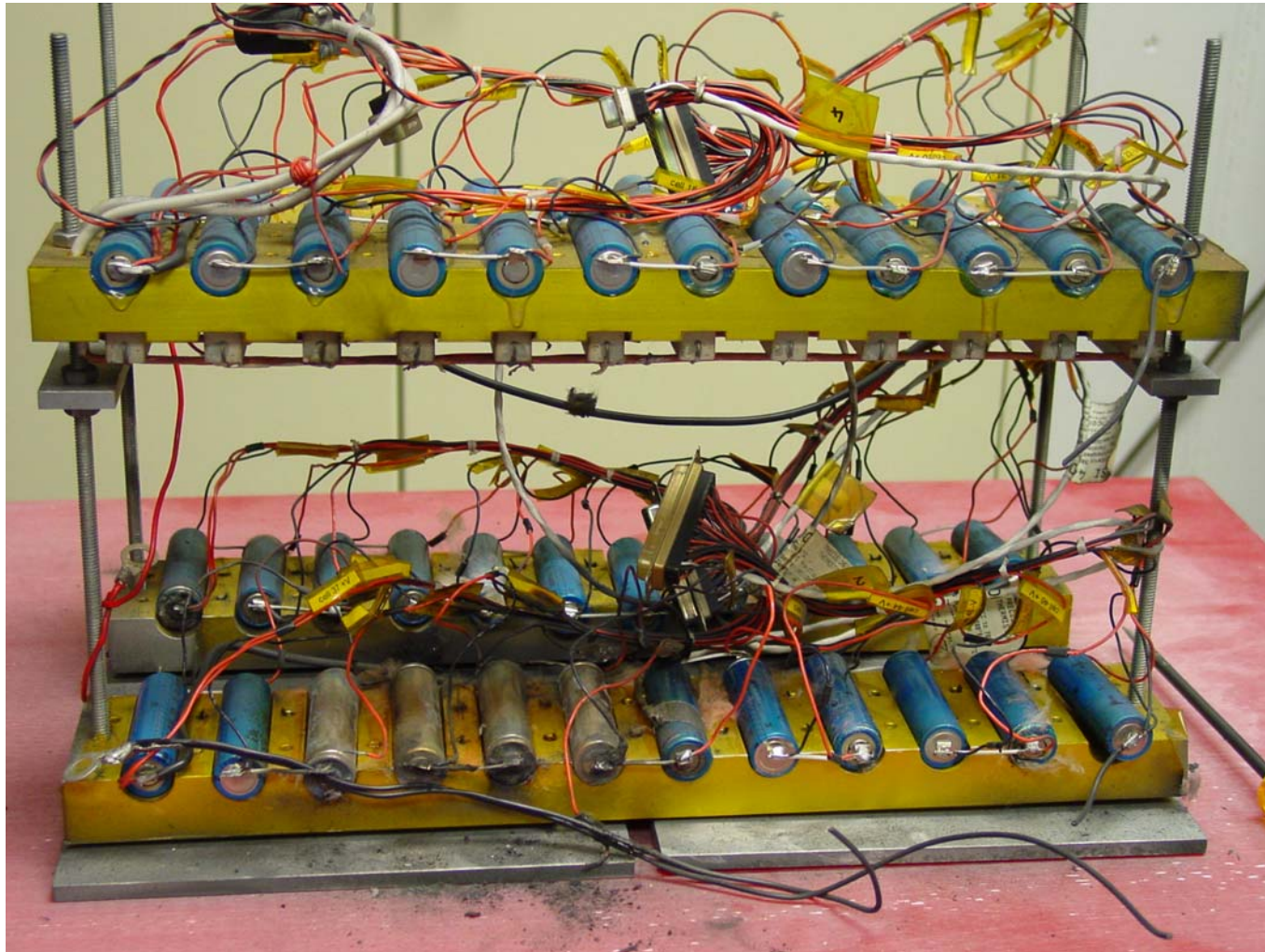


Long String Test



- 24s x 2p test battery
 - Previously used for convergence tests
- Charge to 105.6V, 4.4V/cell
- 'Admirals' test
- Short it
- Low-rate voltage sampling on each cell + current
- Considerable damage

24s x 2p Battery - after



Condition of Cells after the Test

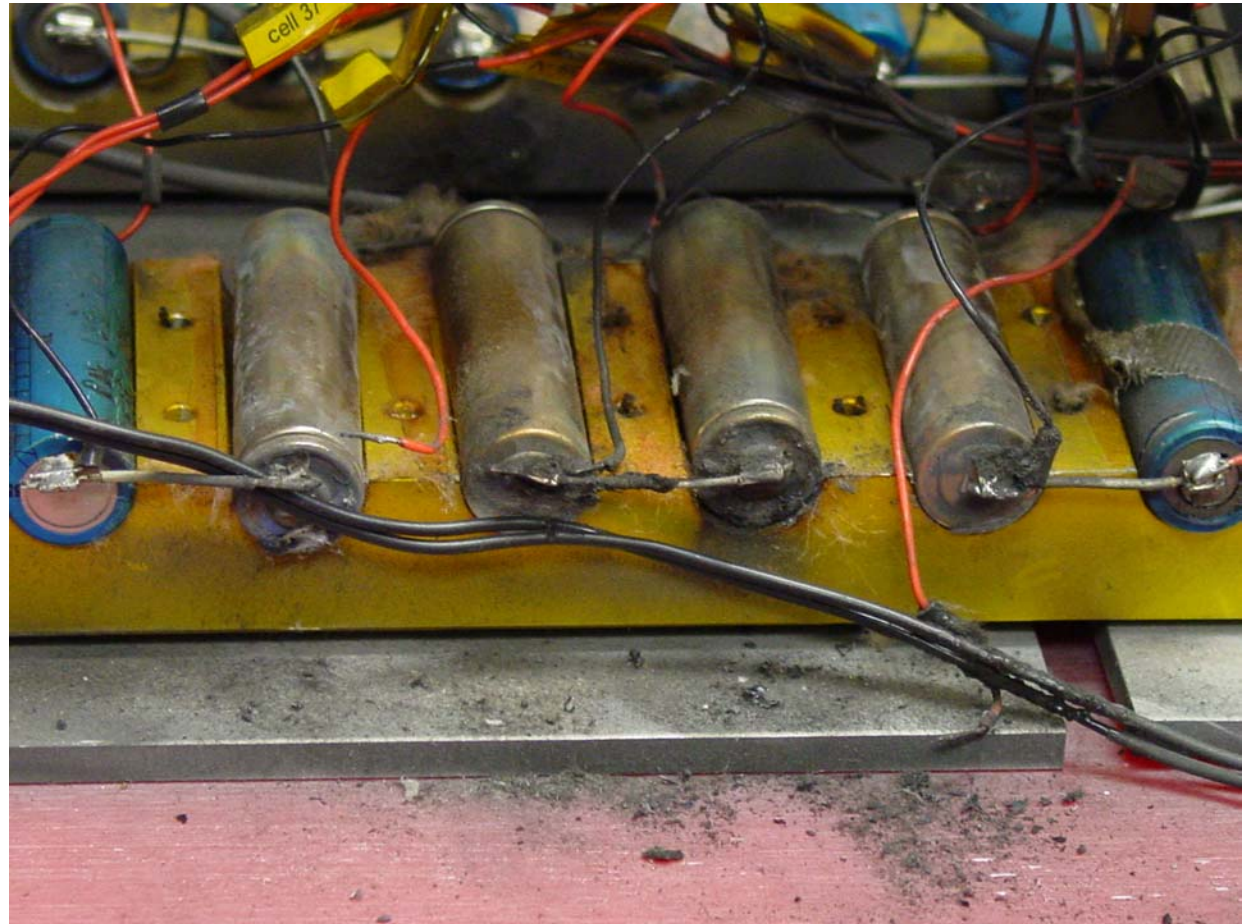


<u>State</u>	<u>No. of Cells</u>
Operating	12
No volts	27
Leaks/vents	25
Wrapper damage	23
Meltdown	4 (cells 39 – 42)

Cells 39 - 42



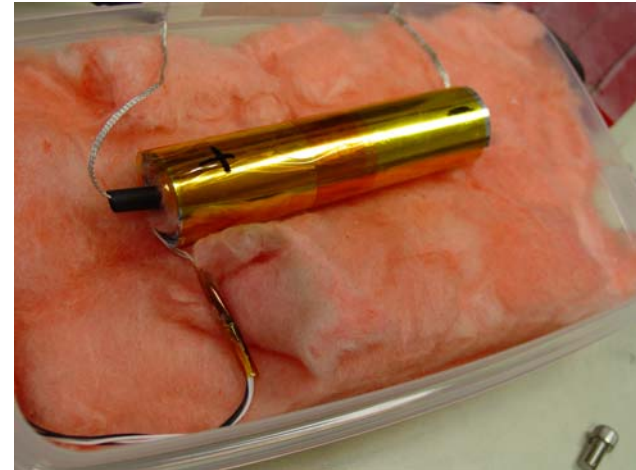
- Cans ~300°C
- Lost ~10g
- Aluminum internal tabs melted (>600°C)



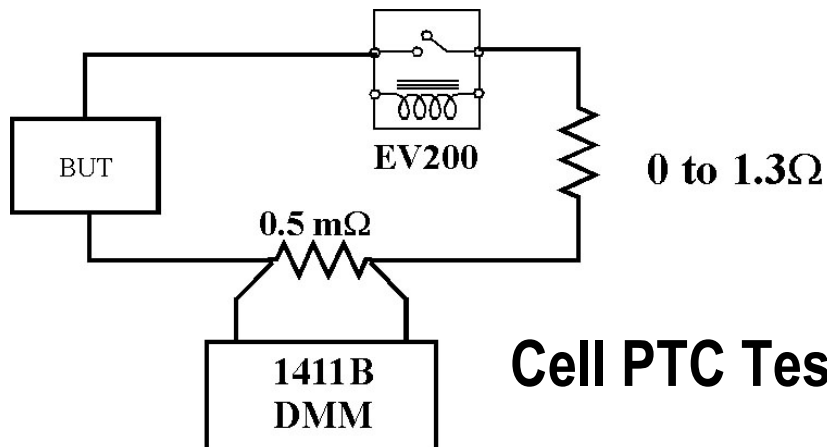
Single-Cell Tests



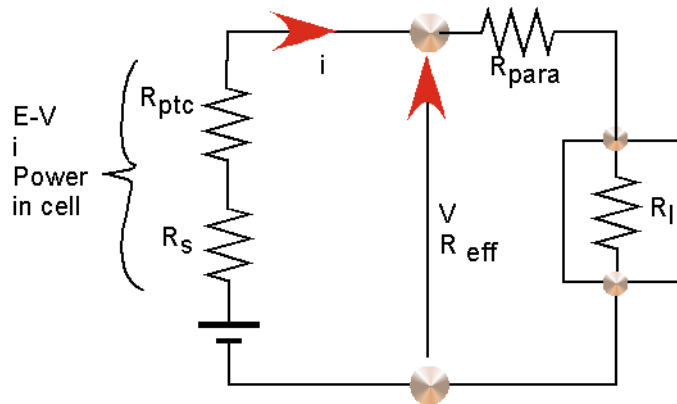
- Aim to understand the PTC
- Fully charged cells, 20°C
- Shorts from 0.5 mΩ to 1.3 Ω
- Cells insulated
- Measured current, voltage, time
- Estimated cell Soc, cell Rs, PTC resistance



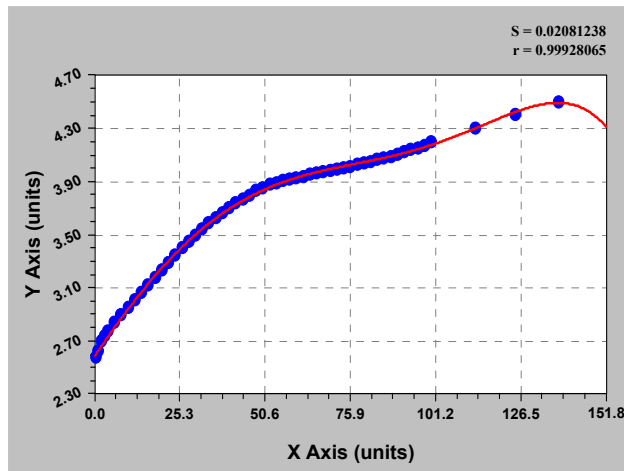
Cell partly installed



PTC Equivalent Circuit



Cell state estimated using initial state + SoC EMF relationship



6th Degree Polynomial	
Coefficient Data:	
a =	2.586134
b =	0.037551
c =	-0.00017
d =	-2.95E-06
e =	2.02E-08
f =	1.38E-10
g =	-9.52E-13

Set Parameters

Cell initial state e.g 4.385V EMF

Load Resistance

Measured parameters are:

V, cell terminal volts (mVolts)

I, cell current (Amps)

T, cell temperature (Temp)

Derived parameters are:

Actual presented load resistance (R eff)

Ah out of cell

Wh dissipated in cell

State of charge

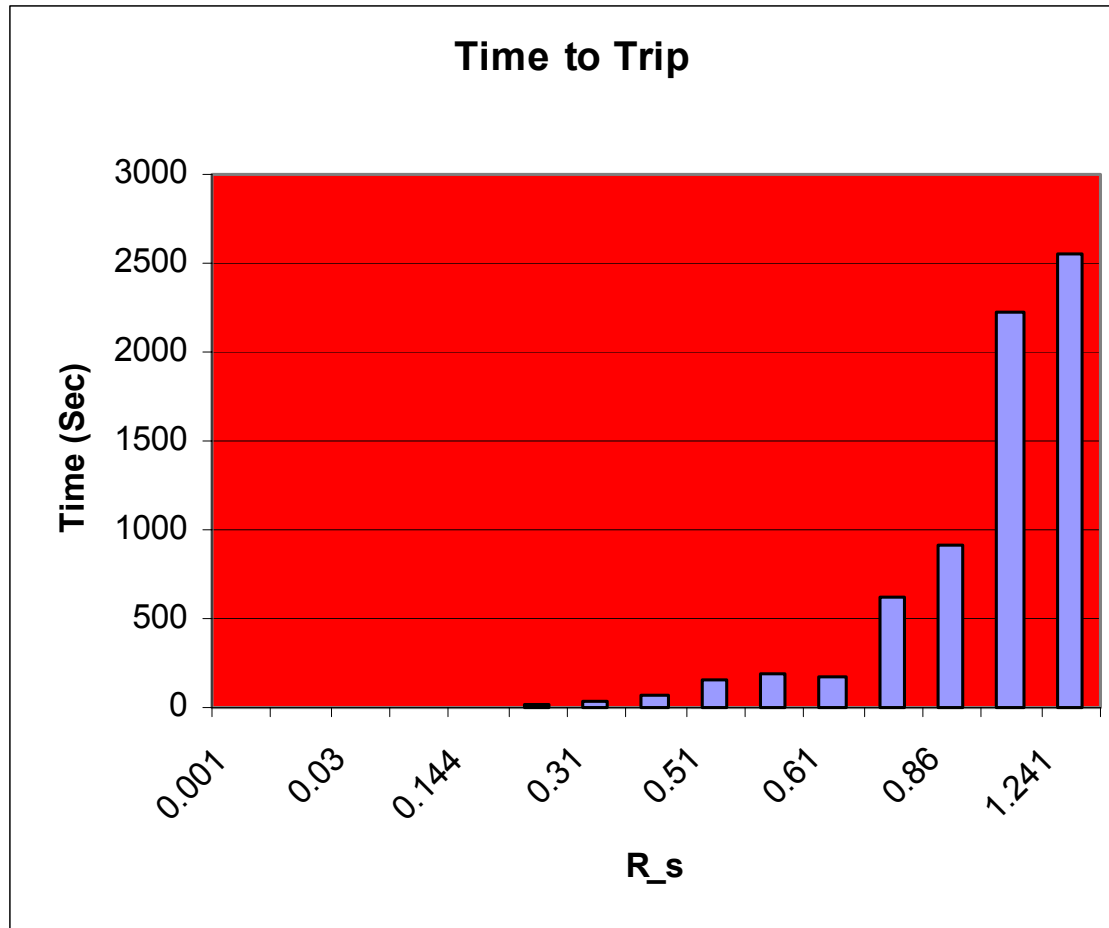
Cell EMF

Cell dissipation, PTC dissipation

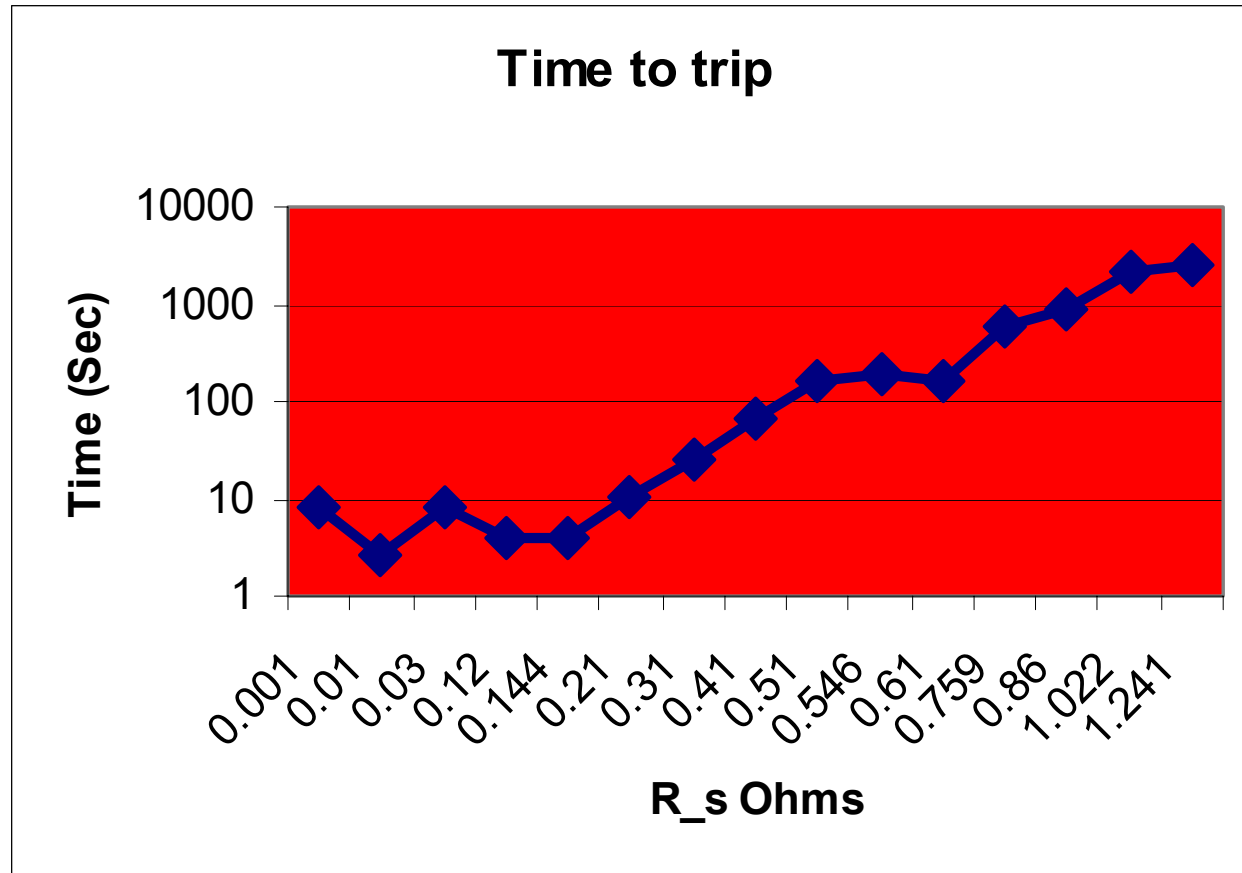
Cell dissipation energy (W-h)

Extra parasitic resistance (Rpara)

Single Cell Time-to-trip (linear)



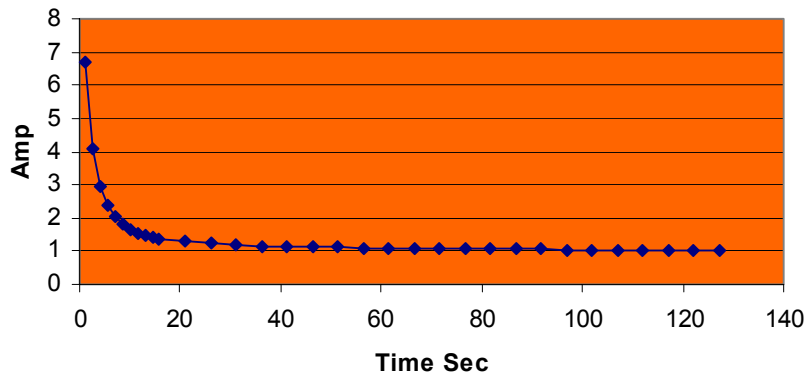
Single Cell Time-to-trip (log)



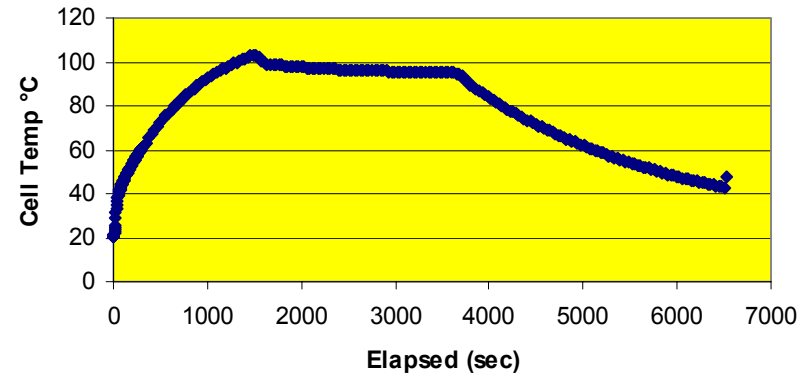
Typical Data – hard short



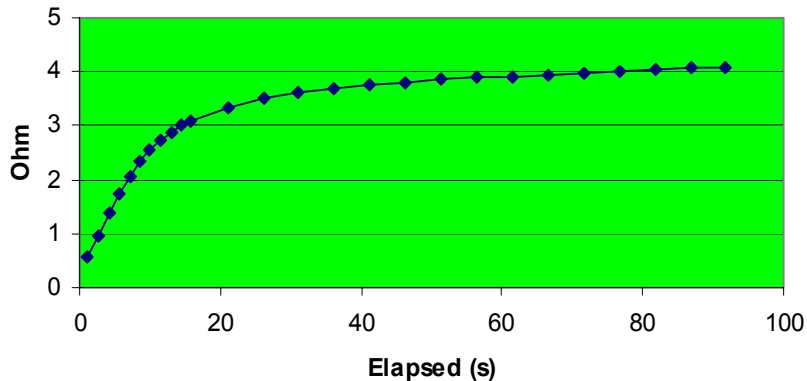
PTC Test 33 Current



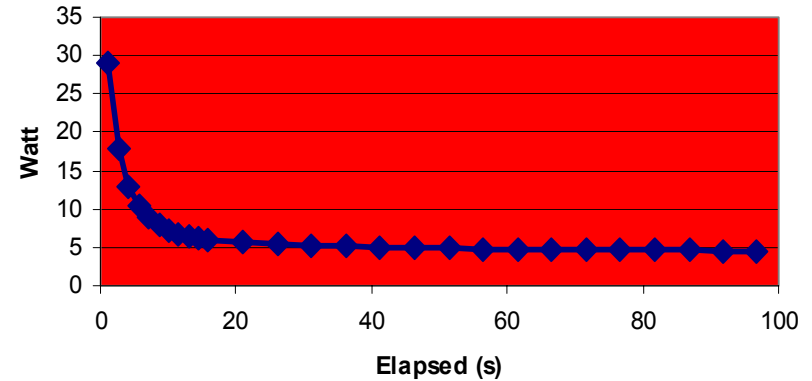
PTC Test 33 (hard short) Temp.



PTC Test 33 Rptc



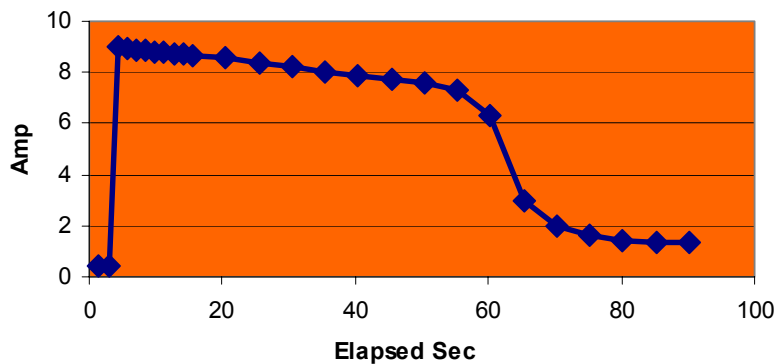
PTC test No 33, PTC Dissipation



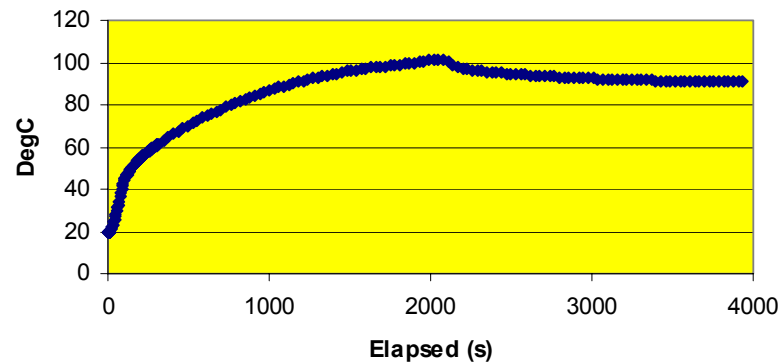
Typical Data – 0.41 Ohm



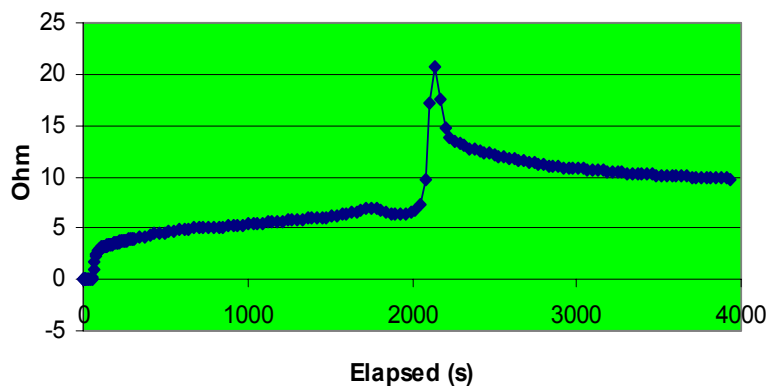
PTC test No 43 Current



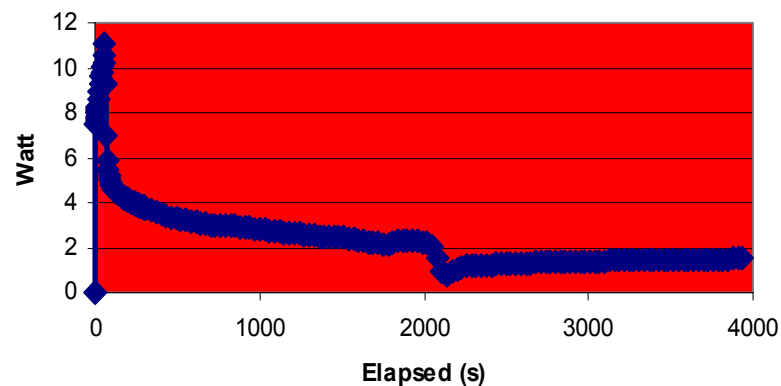
PTC test No 43 - temperature



PTC Test No 43, Rptc



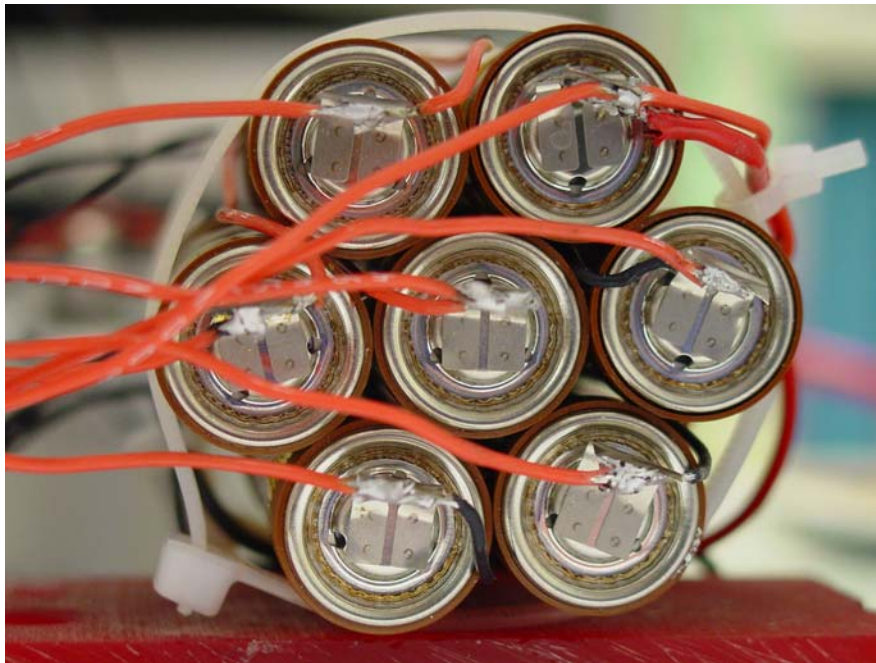
PTC Test No 43, PTC dissipation



Short-String Tests

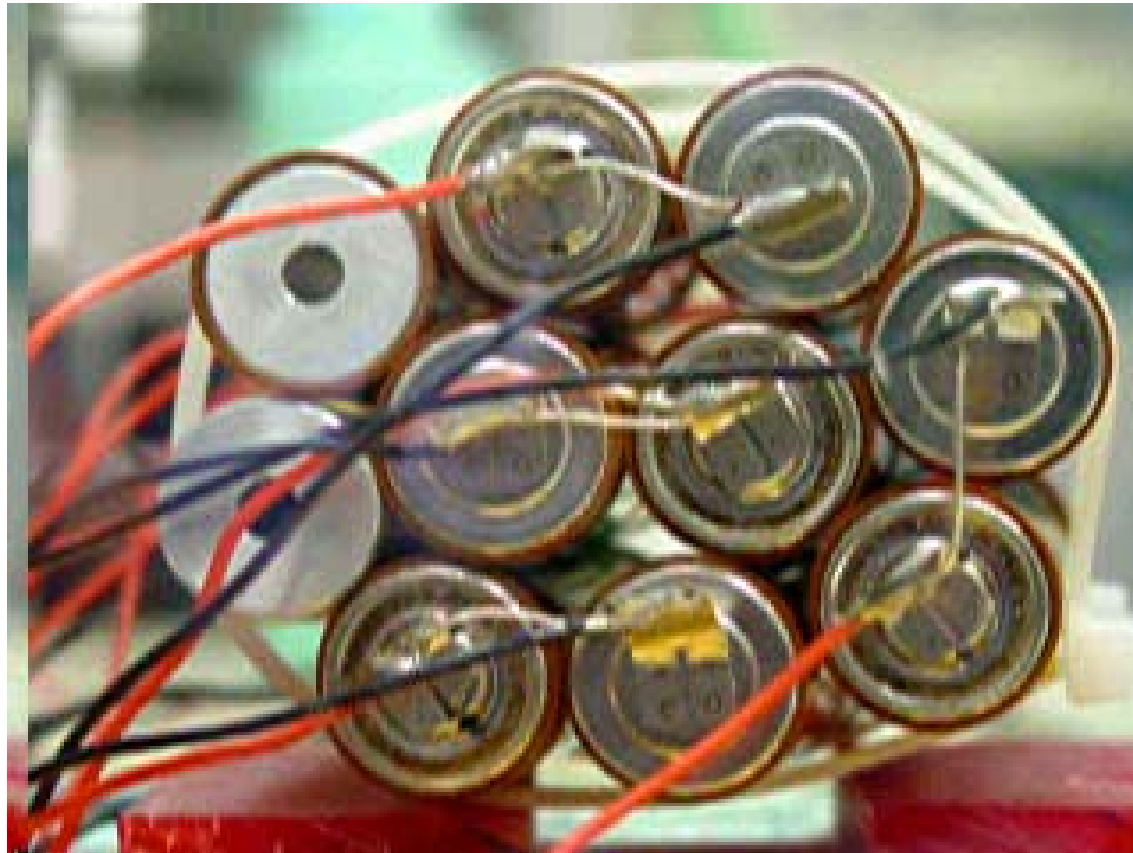


- 6, 7 and 8s strings shorted (hard shorts)
- 6s and 7s strings shut down gracefully
- With 8s, 2 out of 3 'sparked'



**7S cell bundle ready
for test**

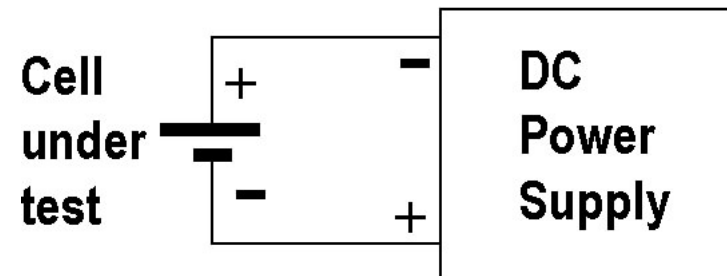
8s Test No 1



Single-cell tests with reverse voltage



- Tests conducted by NASA-JSC
- Aim to simulate the sacrificial cell by applying a negative voltage
- Use high current power supply



Single-cell results - 1



Cell No.	Temp at start	Current during trip	Time to trip (Sec)	Voltage after trip	Current after trip	Notes	DPA Notes
61	amb	18A	2.5	0.0V 1.0 cells	1.27A	No fail	
49	amb	15 A	6.056	-25.4 V 6.8 cells	0.25 A	No fail.	
60	amb	15 A	5.18	-32.36 V 8.4 cells	3.6 A	Failed after less than 1 second of -32 V then seal failure after 8 seconds	Damage to PTC and shorted seal
66	amb	15 A	4.905	-30.6 V 8.0 cells	0.23 A	Failure 43 sec after trip PTC end stayed at 70C after external supply removed	Minor damage to PTC and shorted seal

Single-cell results - 2



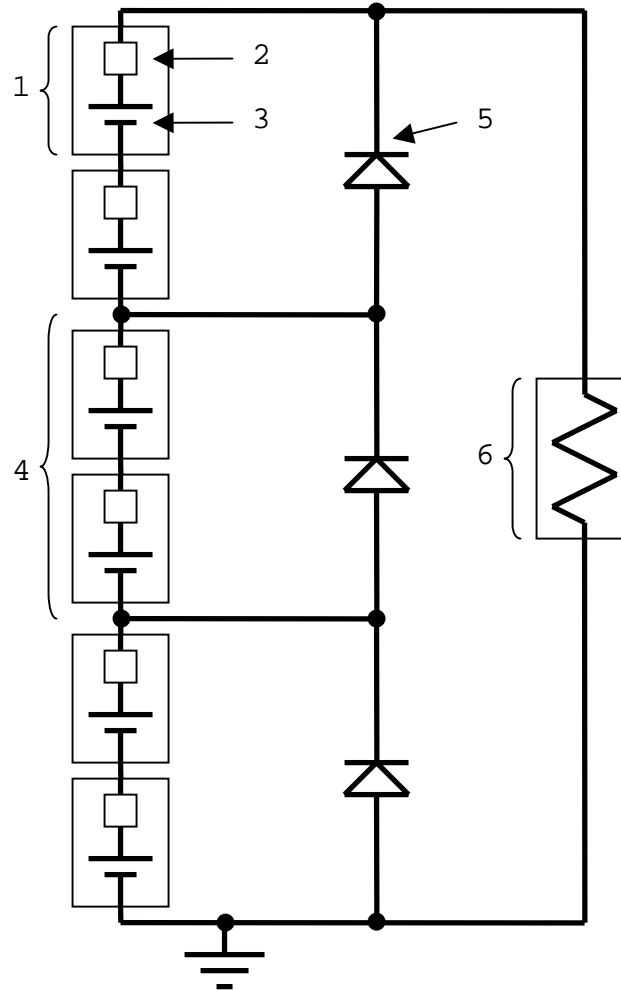
Cell No.	Temp at start	Current during trip	Time to trip (Sec)	Voltage after trip	Current after trip	Notes	DPA Notes
57	amb	15 A	4.383	-22.5 V 6.2 cells	0.26 A	No failure	
55	65C	13.1 A	0.9 -o 1.2	-27.3 V 7.3 cells	0.19 A	Failure after 90 sec of -27.3 V PTC end stayed at 84C after external supply removed and during purge.	No damage to PTC but seal shorted under curled over crimp edge. Thermal evidence that cell discharged itself slowly through PTC and this short.
51	65C	8.5 A	0.788	-26.8 V 7.2 cells	0.06 A	No Failure	

Single-cell tests - observations



- Temperature at PTC shoots up very quickly when PTC trips.
- Maximum temperatures on the outside of the case at the crimp go up above 200°F (95°C)
- Collateral damage caused to crimp seal
- Tests confirmed that ~7s was 'marginally safe'
- 9 Amp diodes appear to handle the ~60A inrush current

Component Parts

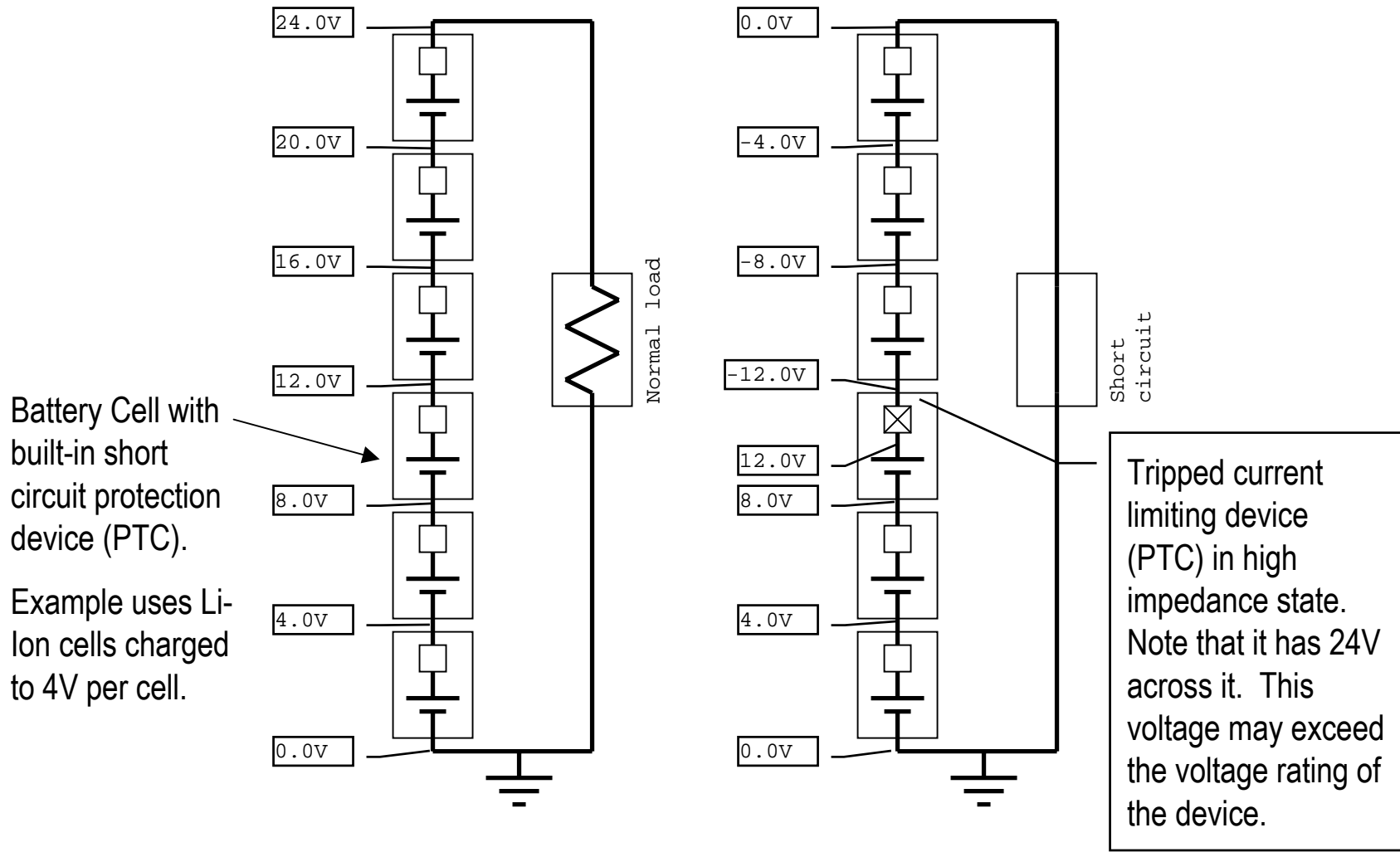


1. Battery cell with built-in short circuit protection.
2. Internal short circuit protection device (PTC). May be similar to Raychem Polyswitch.
3. Electrochemical part of cell (provides electromotive force)
4. Substring
5. Diode
6. Load.

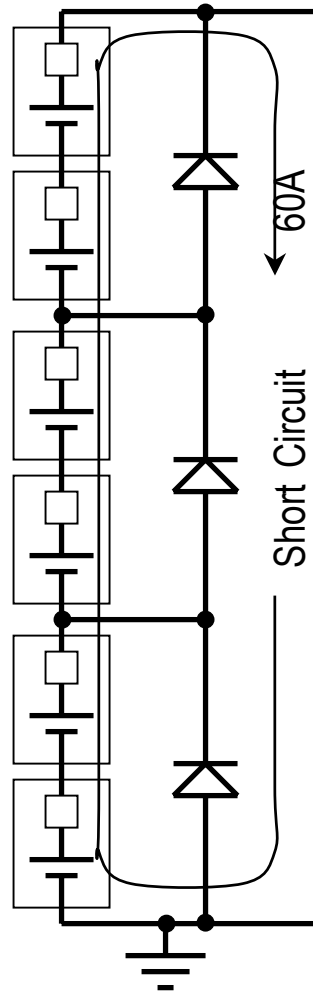
Notes:

- A. More than two battery cells per substring may be used.
- B. More than 3 substrings may be used.
- C. The example battery system presented here is of limited size and complexity for clarity.

High voltage on PTC during Short Circuit



Trip Sequence – initial stage

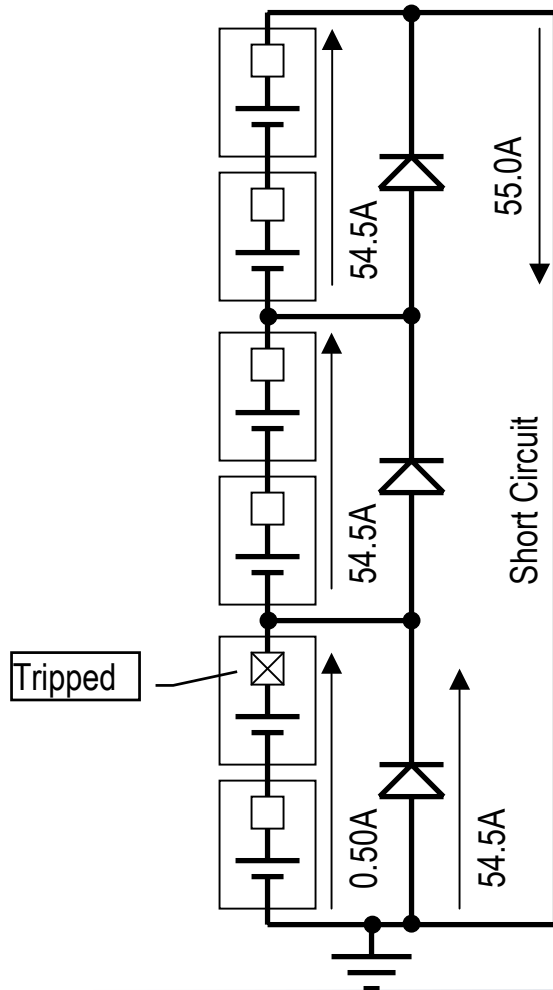


Short circuit appears. All PTC short circuit protection devices start heating up.

Notes:

1. No current through diodes yet.
2. Short circuit current is limited by cell impedances and cold PTC impedances.
3. This stage may last several seconds, depending on PTC characteristics.

Trip Sequence – later stages



First PTC trips, shunting current through diode.

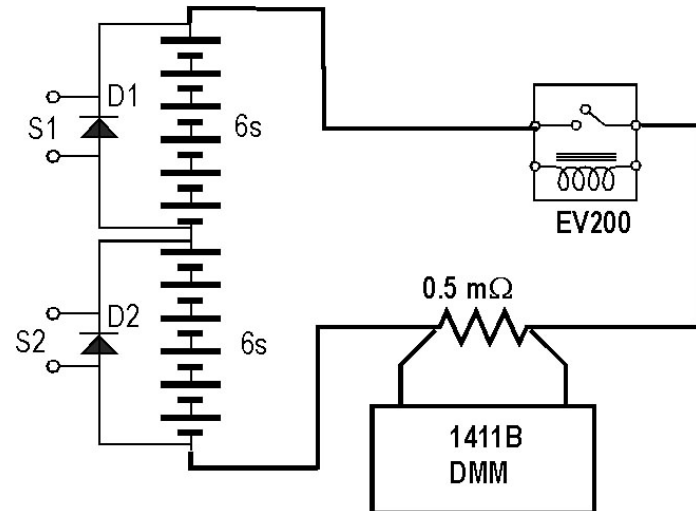
Note:

1. Small current flows through shorted substring, keeping PTC tripped.
2. Current through short is reduced, but not dramatically, since the current is still basically limited by the cell impedances. Other substrings have not tripped yet.
3. Maximum voltage across tripped PTC is two cells worth plus diode drop.
4. Diode takes almost maximum short circuit current until trip sequence is complete.
5. Which substring trips first depends on device tolerances.
6. The other substrings follow.

12s Short-Circuit Test- with diodes



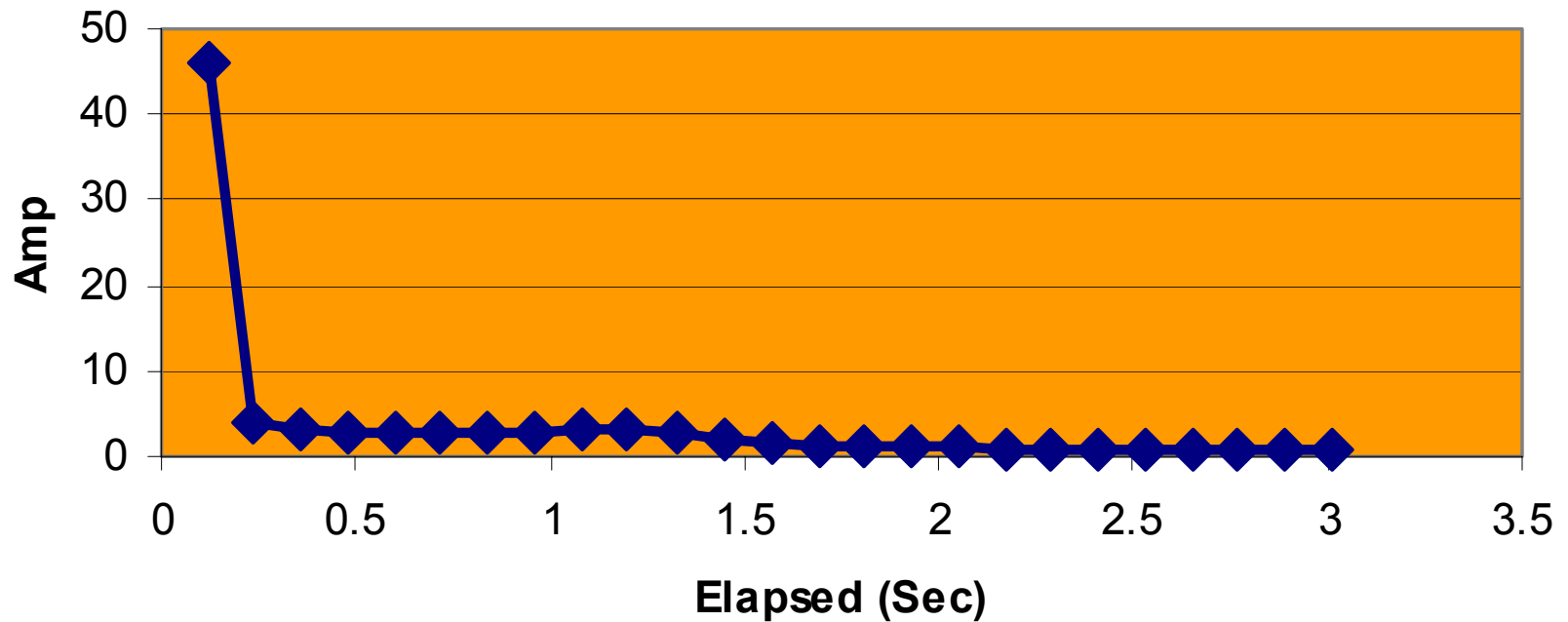
- 12s bundle configuration
- 9 Amp Schottky diodes
- Dead short
- Monitor current and diode voltages



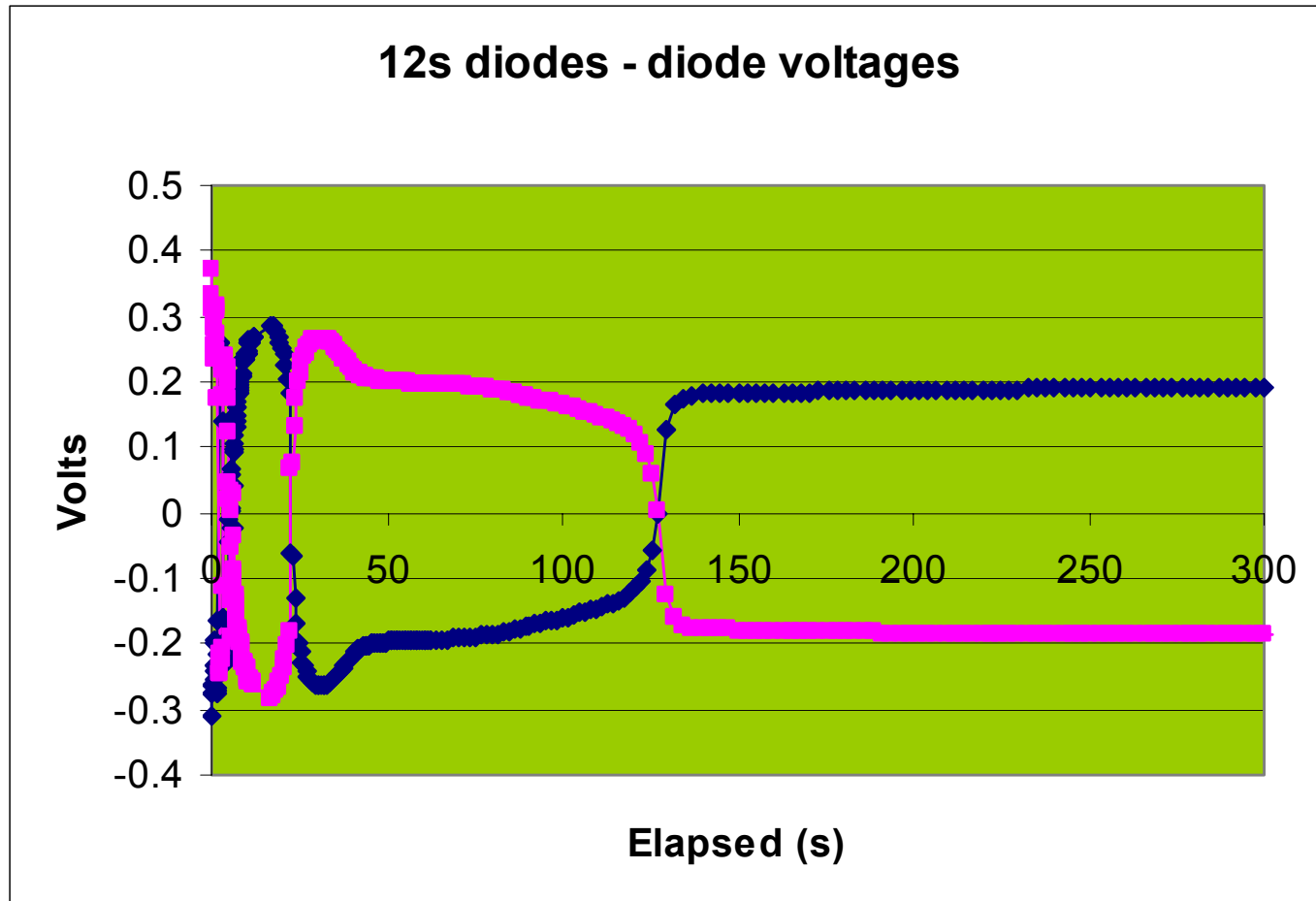
12s Short-Circuit - current



12s String with diodes



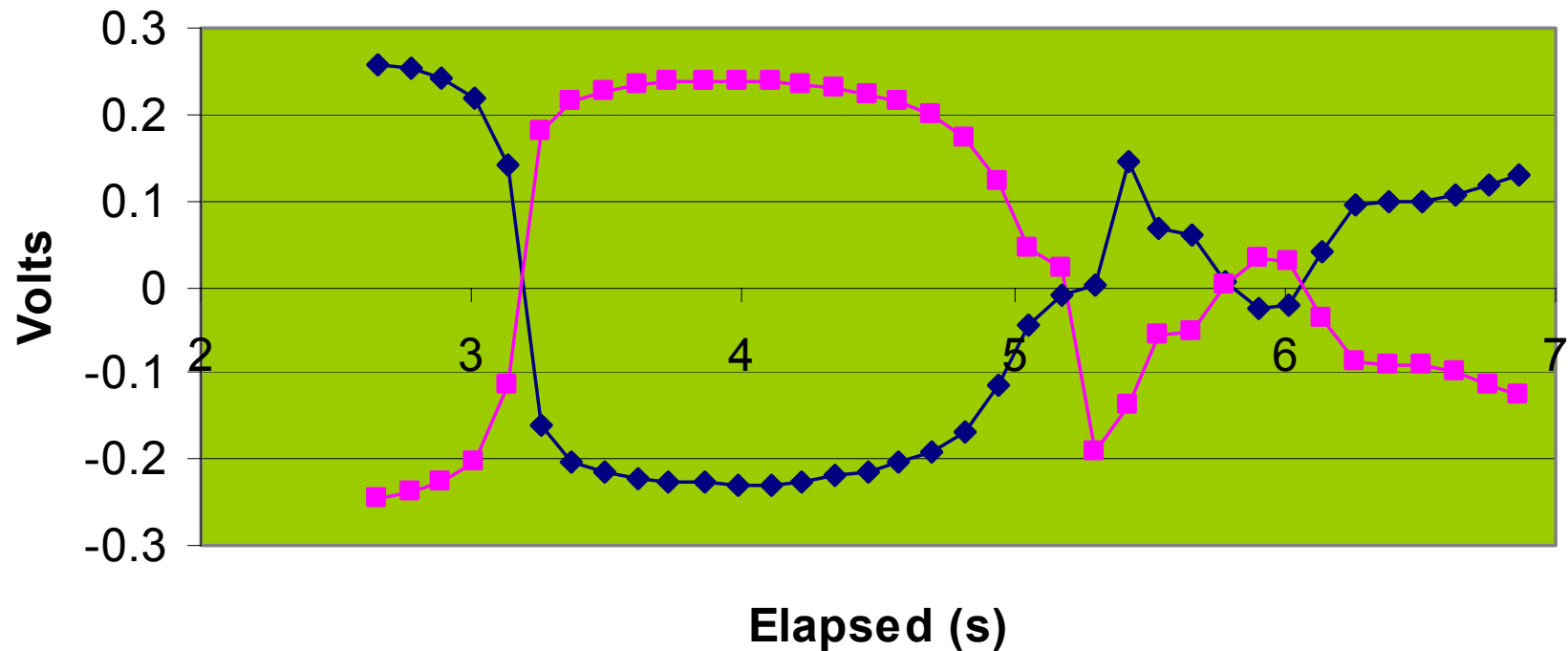
12s Test – Diode Voltage -1



12s Test – Diode Voltage -2



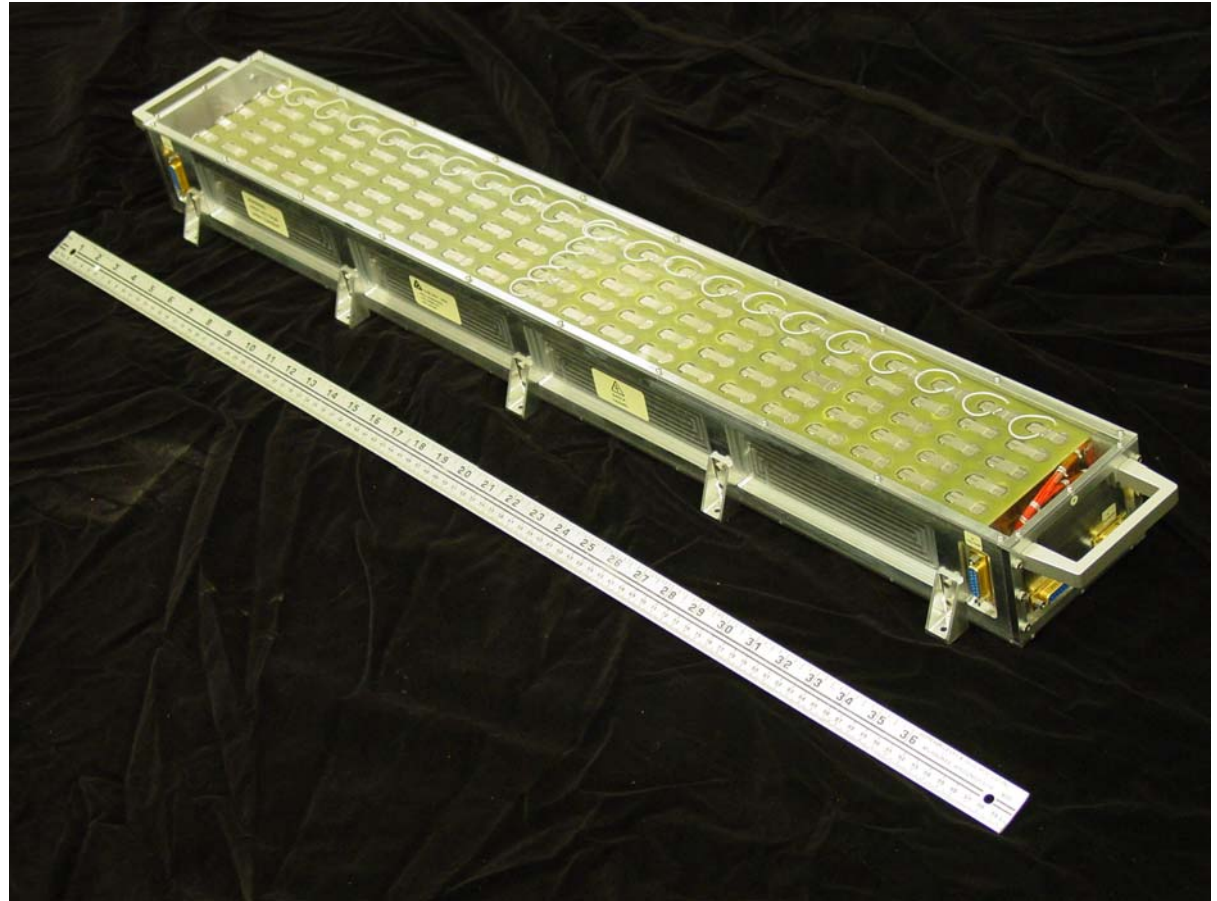
12s diodes - diode voltages

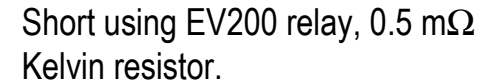


41s x 5p Short-Circuit

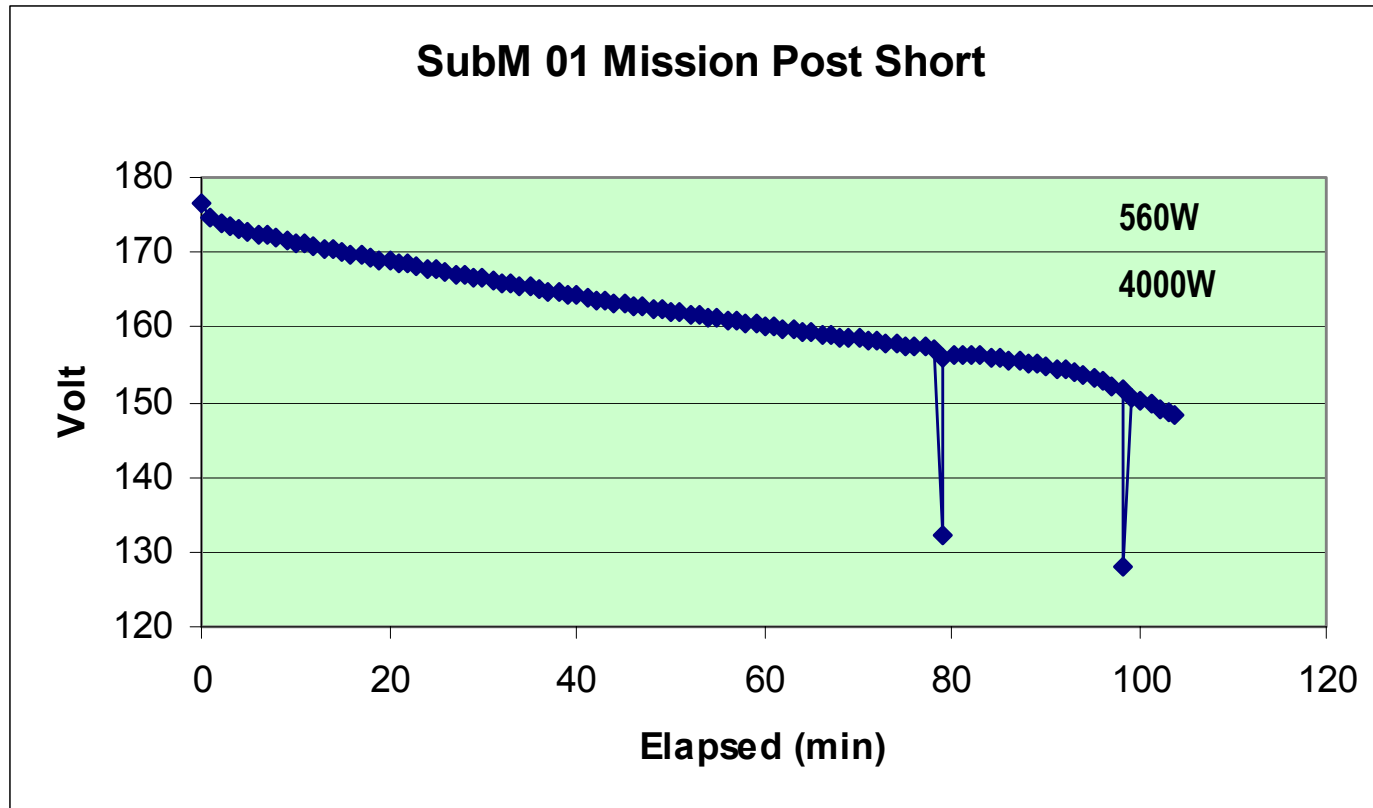


- EAPU GTM
- Charge to 180.4V
- Short
- Successful
 - no damage
 - no venting
 - still works





Post-short EAPU Mission Cycle



Battery charged to pre-launch state, including losses

Launch and de-orbit run concatenated

Diode Protection Scheme - summary



■ Advantages:

- Increases robustness
- Protects PTCs – allows them to operate normally
- Allows operation of cells within voltage environment that they were designed for (short series strings, not long series strings).
- Bypass diodes across substrings help with other high impedance cell conditions (tripped CID, shutdown separator, discharged cell) by holding down max. voltage.

■ Disadvantages:

- Added components increase size, weight and complexity.
- Diodes sized to take maximum current are not small.
 - Testing will allow us to optimize diode sizing.

Conclusions



- We have gained considerable insight into cell PTC operation
 - Maximum voltage rating of the PTC at 65°C is 31V
 - Once tripped, PTCs are more tolerant to higher voltages
- Even without diode protection, a short with a small-cell battery is not a violent event
- The diode protection scheme works
 - Using commercial Schottky diodes
- The battery is usable afterwards
- The scheme is being implemented on current modules
- Further short-circuit tests are planned
 - To validate function in worst-case conditions
 - To better understand cell failure mechanisms